Accessing directly the strange quark content of the proton at HERA

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We investigate a double-spin asymmetry for the semi-inclusive Λ hyperon production in the longitudinally deep inelastic lepton-proton scattering, the sign of which can provide us with important information about the strange quark helicity distribution in the proton. On the basis of the interpretation of the longitudinal deep inelastic lepton-nucleon scattering data as a negative strange quark polarization in the proton and the preliminary results on the measurement of the longitudinal Λ polarization at the Z resonance in electron-positron annihilation, we predict a minus sign for the suggested observable. The experimental condition required for our suggestion is met by the HERA facilities, so the asymmetry considered can be measured by the HERMES experiments at HERA in the near future.

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Since the announcement of the famous European Muon Collaboration (EMC) experiment results [1], the extensive interest in the physics community has been attracted [2] by the proton spin structure. Besides the EMC data, the ensuing experiments [3] also indicate that the strange quarks and antiquarks in the proton possess a net negative polarization opposite to the proton spin. However, other possible interpretations such as the polarized glue in the proton [4] have been competing with this allegation. Therefore, it is imperative to invent some machineries to access independently the strange contents of the proton.

Considering the self-analyzing property of the Λ hyperon, a group of authors have discussed the possibility to use the Λ polarization as a strange quark polarimeter to detect the strange quark polarization in the proton. Based on an extrapolation of the present knowledge of polarized structure functions [1,3], Ellis et al. [5] suggested a model for the strangenees of the proton, in which a valence quark core with the naive quark model spin content is accompanied by a spin-triplet $\bar{s}s$ pair. Furthermore, the strange antiquark is supposed to be negatively polarized, motivated by chiral dynamics, and likely the strange quark, motivated by $^3P_0$ quark condensation in the vacuum. In such a model, Alberg, Ellis, and Kharzeev [6] pointed out that the measurement of target spin depolarization parameter in the $\bar{p}p \to \bar{\Lambda}\Lambda$ may construct a test of the polarization state of the strange quarks in the proton. Following this line, Ellis, Kharzeev and Kontzinian [7] made predictions for the polarization of the Λ hyperons semi-inclusively detected in the *target fragmentation region*. At the same time, Lu and Ma [8] investigated the polarization of the Λ particles produced in the *current fragmentation region* within the framework of the quark-parton model. Assuming an unpolarized lepton beam and a longitudinally polarized proton target, they found that the sign of the Λ polarization in the current fragmentation region can supply us with important information about the strange quark polarization in the proton.

At present, the most promising deeply inelastic scattering experiments are being done at DESY HERA, where both the lepton beam and nucleon target are longitudinally polarized. Therefore, it is desirable to search for some observables accessible at the HERA facilities to probe the strange quark spin in the proton. The HERA experiments are performed [9] by

keeping the beam polarization unchanged and reversing the target polarization as required. In this Letter, we completely conform to such experimental conditions and investigate the implication of the possible negative strange quark polarization to the semi-inclusively detected Λ particles. Our findings are positive, i.e., there exists a spin asymmetry for the semi-inclusive Λ hyperon production when both the lepton beam and proton target are longitudinally polarized. The sign of this quantity is contingent on that of the strange quark polarization in the proton.

More generally, we consider the semi-inclusive Λ production by the longitudinally deep inelastic lepton-nucleon scattering

$$l(p_l, s_l) + N(p_N, s_N) \to l(p_l') + \Lambda(p_\Lambda, s_\Lambda) + X,$$

where the particle momenta and covariant spin vectors are self-explanatory. As a first approximation, we adopt the one-photon exchange approximation, in which the proton structure is probed by a virtual photon of momentum $q = p_l - p_l'$. Then, the cross section is related to the Lorentz contraction between the leptonic tensor and hadronic tensor.

As usual, the leptonic tensor is taken as

$$L^{\mu\nu}(q, p_l, s_l) = \frac{q^2}{2} g^{\mu\nu} + 2p_l^\mu p_l^\nu - p_l^\mu q^\nu - q^\mu p_l^\nu + 2im_l \varepsilon^{\mu\nu\tau\rho} q_\tau s_{l\rho}, \tag{1}$$

while the hadronic tensor is defined

$$\begin{aligned} W^{\mu\nu}(q, p_N, s_N, p_\Lambda, s_\Lambda) \equiv & \frac{1}{4\pi} \sum_X \int d^4\xi \exp(iq \cdot \xi) \\ & \times \langle p_N, s_N | j^\mu(0) | \Lambda(p_\Lambda, s_\Lambda), X\rangle \langle \Lambda(p_\Lambda, s_\Lambda), X | j^\nu(\xi) | p_N, s_N \rangle, \end{aligned} \tag{2}$$

where the electromagnetic current is defined as $j_\mu = \sum_a e_a \bar{\psi}_a \gamma_\mu \psi_a$ with a the quark flavor index and e_a the quark charge in unit of the electron charge. We normalize the spin vector as $s \cdot s = -1$ for the pure state of a spin-half fermion. In the forthcoming presentation, the longitudinal spin four-vector s is related to the particle helicity h via

$$\text{limit}_{m\to 0}\; ms^\mu = hp^\mu, \tag{3}$$

where m is the fermion mass and p^μ the momentum.

We adopt the conventional scalar variables:

$$x_B = \frac{-q^2}{2p_N \cdot q}, \ y = \frac{p_N \cdot q}{p_N \cdot p_l}, \ z = \frac{p_N \cdot p_\Lambda}{p_N \cdot q}. \tag{4}$$

Correspondingly, the cross section can be written as

$$\frac{d\sigma(s_l, s_N, s_\Lambda)}{dx_B dy dz d^2\mathbf{p}_{\Lambda\perp}} = \frac{\alpha^2 y}{8\pi^2 z Q^4} L_{\mu\nu}(q, p_l, s_l) W^{\mu\nu}(q, p_N, s_N, p_\Lambda, s_\Lambda), \tag{5}$$

where $Q = \sqrt{-q^2}$ and $\mathbf{p}_{\Lambda\perp}$ is the components of the transverse Λ momentum relative to the axis of the quark fragmentation jet.

The hadronic tensor contains all the information about the proton structure and Λ hyperon production. Because of the lack of methods to treat nonperturbative effects, the general strategy so far is to factorize [10] the hadronic tensor into the long- and short-distance parts. The long-distance matrix elements encode the information on the proton structure and the hyperon production by parton hadronization whereas the short-distance coefficients describes the hard partonic interaction. We will work at the leading twist factorization, which is equivalent to the quark-parton model prescription without including any higher-order effects, so the corresponding nonperturbative matrix elements can be interpreted as the quark distribution and fragmentation functions in the quark parton model. For our purpose to elucidate the main physics, it is enough to adopt such a lowest-order approximation.

At the leading order and leading twist, only the lowest-order diagram shown in Fig. 1 makes contributions to the hadronic tensor:

$$\begin{aligned}\int W^{\mu\nu}(q, p_N, s_N, p_\Lambda, s_\Lambda) \frac{d^3 p_\Lambda}{2E_\Lambda (2\pi)^3} &= \frac{1}{4\pi} \int \frac{d^4 p_\Lambda}{(2\pi)^4} (2\pi) \delta(p_\Lambda^2 - M_\Lambda^2) \\ &\times \int \frac{d^4 k}{(2\pi)^4} \sum_a e_a^2 \mathrm{Tr}\left[T_N^a(k, p_N, s_N) \gamma_\mu T_\Lambda^a(k+q, p_\Lambda, s_\Lambda) \gamma_\nu\right],\end{aligned} \tag{6}$$

where two nonperturbative matrices (in the Dirac space) are defined as

$$T_N^a(k, p_N, s_N)_{\alpha\beta} = \int d^4\xi \exp(ik \cdot \xi) \langle p_N, s_N | \bar{\psi}_\beta^a(0) \psi_\alpha^a(\xi) | p_N, s_N \rangle, \tag{7}$$

$$T_\Lambda^a(k, p_\Lambda, s_\Lambda)_{\alpha\beta} = \sum_X \int d^4\xi \exp(-ik \cdot \xi) \langle 0 | \psi_\alpha^a(0) | \Lambda(p_\Lambda, s_\Lambda), X \rangle \langle \Lambda(p_\Lambda, s_\Lambda), X | \bar{\psi}_\beta^a(\xi) | 0 \rangle. \tag{8}$$

For the lowest-order diagram, its leading twist contributions can be extracted most efficiently by use of the collinear expansion technique [11], i.e., carrying out an expansion of parton momenta with respect to their components collinear with the corresponding hadron momenta. In this work, we restrict ourselves with the Λ production in the current fragmentation region so that the effects of the Λ hyperon mass can be ignored and the transverse Λ momentum can be safely integrated out. Undergoing the standard procedure [12,13] to separate the nonperturbative matrix elements from the hard partonic interaction part, we obtain the following leading twist factorization results:

$$\begin{aligned}\int W^{\mu\nu}(q,p_N,h_N,p_\Lambda,h_\Lambda)d^2\mathbf{p}_{\Lambda\perp} = &\frac{1}{2zp_N\cdot q}\sum_a e_a^2[f_1^a(x_B)\hat{f}_1^a(z)(-p_N\cdot p_\Lambda g^{\mu\nu}+p_N^\mu p_\Lambda^\nu+p_\Lambda^\mu p_N^\nu)\\ &+ih_N g_1^a(x_B)\hat{f}_1^a(z)\varepsilon^{\mu\nu\lambda\sigma}q_\lambda p_{N\sigma}+ih_\Lambda f_1^a(x_B)\hat{g}_1^a(z)\varepsilon^{\mu\nu\lambda\sigma}q_\lambda p_{\Lambda\sigma}\\ &+h_N h_\Lambda g_1^a(x_B)\hat{g}_1^a(z)(-p_N\cdot p_\Lambda g^{\mu\nu}+p_N^\mu p_\Lambda^\nu+p_\Lambda^\mu p_N^\nu)]. \end{aligned} \tag{9}$$

where $f_1(x)$ and $g_1(x)$ are the quark momentum distribution and quark helicity distribution in the proton, $\hat{f}_1(x)$ and $\hat{g}_1(x)$ are the spin-independent and longitudinal spin-dependent quark fragmentation functions for inclusive Λ production. (We follow Jaffe and Ji's notations about the quark distribution functions [12] and fragmentation functions [13].) As a matter of fact, eq. (9) can also be derived from the quark-parton model.

Substituting eqs. (1) and (9) into (5), we deduce the following expression for the cross section:

$$\begin{aligned}\frac{d\sigma(h_l,h_N,h_\Lambda)}{dx_B dy dz} = &\frac{\alpha^2}{16\pi^2 yzQ^2}\sum_a[(y^2-2y+2)f_1^a(x_B)\hat{f}_1^a(z))\\ &+h_N h_\Lambda(y^2-2y+2)g_1^a(x_B)\hat{g}_1^a(z)+h_l h_N y(2-y)g_1^a(x_B)+h_l h_\Lambda y(2-y)\hat{g}_1^a(z)]. \end{aligned} \tag{10}$$

For the HERA experiments, both the lepton beam and nucleon target are in their helicity states. We consider the polarization of the detected Λ hyperons, which is defined as

$$P_\Lambda(h_l,h_N)\equiv\frac{d\sigma(h_l,h_N,+)-d\sigma(h_l,h_N,-)}{d\sigma(h_l,h_N,+)+d\sigma(h_l,h_N,-)}, \tag{11}$$

where $\pm$ are shorthand for $\pm\frac{1}{2}$. From eq. (10), one can obtain

$$P_\Lambda(h_l,h_N)=\frac{\sum\limits_a e_a^2[h_N(y^2-2y+2)g_1^a(x_B)\hat{g}_1^a(z)+h_l y(2-y)\hat{g}_1^a(z)]}{\sum\limits_a e_a^2[(y^2-2y+2)f_1^a(x_B)\hat{f}_1^a(z)+h_l h_N y(2-y)g_1^a(x_B)]}. \tag{12}$$

Obviously, the Λ polarization has two sources: the spin transfer from the lepton beam and that from the nucleon target, respectively.

Keeping in mind the valence quark configuration of the Λ hyperon, we may assume *a priori* that the Λ particle is predominantly produced by the current strange quark fragmentation. Then, the flavor summation can be dropped in the above formula and correspondingly we consider only the contributions pertinent to the strange quark. As Burkardt and Jaffe [14] have discussed, the measurement of the longitudinal Λ polarization around the Z resonance in electron-positron annihilation can allow the determination of the $s\to\Lambda$ fragmentation functions, both $\hat{f}_1^s(z)$ and $\hat{g}_1^s(z)$. Since the LEP I collider was operated at the Z resonance and HERA is presently colliding 28 GeV electrons on 820 GeV protons, the corresponding processes are commonly believed to fall into the reign in which perturbative QCD works. Once the $s\to\Lambda$ fragmentation functions are obtained by analyzing LEP-I data, one can evolve them to the HERA energy scale by the Altarelli-Parisi equations [16]. With such inputs, the measurement of the Λ polarization at HERA will make possible an independent extraction of the strange quark helicity distribution $g_1^s(x)$. However, this will not be an easy work because of the experimental complexities.

For our understanding of the strangeness in the proton, the sign of the net strange quark polarization may be more important than its precise x-dependence. Our finding is that the double-spin asymmetry

$$A(h_l)\equiv\frac{d\sigma(h_l,+,+)-d\sigma(h_l,+,-)-d\sigma(h_l,-,+)+d\sigma(h_l,-,-)}{d\sigma(h_l,+,+)+d\sigma(h_l,+,-)+d\sigma(h_l,-,+)+d\sigma(h_l,-,-)} \tag{13}$$

is sensitive to the sign of $g_1^s(x)$. To see this point, one can insert eq. (10) into (13), obtaining the following simple formula

$$A=\frac{g_1^s(x_B)\hat{g}_1^s(z)}{f_1^s(x_B)\hat{f}_1^s(z)}, \tag{14}$$

in which we again take into account the contributions relevant to the strange quark only. Therefore, although this result is subject to radiative corrections and higher-twist effects,

one can at least anticipate that the measurement of $A(h_l)$ allow the determination of the sign of $g_1^s(x)$.

The measurement of $A(h_l)$ needs to monitor the polarization of the Λ hyperon, so $d\sigma(h_l, h_N, h_\Lambda)$ is not directly measurable. However, the asymmetry $A(h_l)$ can be accessed experimentally. To show this, we cast $A(h_l)$ into the form

$$A(h_l) = \sum_{h_N} \text{sign}(h_N) D(h_l, h_N) P(h_l, h_N), \tag{15}$$

where

$$D(h_l, h_N) \equiv \frac{\sum\limits_{h_\Lambda} d\sigma(h_l, h_N, h_\Lambda)}{\sum\limits_{h'_N, h_\Lambda} d\sigma(h_l, h'_N, h_\Lambda)}. \tag{16}$$

So, $A(h_l)$ can be schematically thought of as being a $D(h_l, h_N)$-weighted "asymmetry" of the Λ polarization when the helicity of the target nucleon is reversed. Obviously, $D(h_l, h_N)$ can be measured by controlling the initial-state beam and target polarizations in the deep inelastic scattering and semi-inclusively detecting a Λ hyperon in the current fragmentation region. Therefore, the asymmetry $A(h_l)$ is an observable experimentally accessible. Hopefully, its measurement can be implemented by the future HERMES experiments [9] at HERA as well as by the future HELP experiment [17] at CERN.

The preliminary results about the longitudinal Λ polarization at the Z resonance at LEP-I have already been existent [15], which imply that the longitudinal spin-dependent $s \to \Lambda$ fragmentation function is positive. Although the data are subjected to refinement, one can be confident that there will not be qualitative changes. If the interpretation is accepted of the longitudinal deeply inelastic scattering data as a net negative strange quark polarization in the proton, we can make a prediction that the considered double-spin asymmetry is negative. The experimental condition required for this spin asymmetry happens to be met at HERA, where one fixes the lepton beam polarization but reverse the target polarization as required so as to measure the longitudinal spin-dependent quark distributions. Considering the large statistics needed, one can at least determine the sign of the strange quark polarization in the proton.

In conclusion, we worked out a leading twist factorized expression for the hadronic tensor for the semi-inclusive Λ production by the longitudinally deep inelastic scattering of leptons off nucleons. Furthermore, we proposed an observable $A(h_l)$, which is simply related to the strange quark distribution functions in the nucleon and the $s \to \Lambda$ fragmentation functions. Provided that the involved fragmentation functions are precisely measured at LEP in the near future, the measurement of the suggested quantity at HERA will allow the determination of the strange quark helicity distribution in the nucleon. Considering the large statistics needed in such experiments, we point out that even the accurate measurements cannot be done on $A(h_l)$, its measured sign can still supply us with very useful information about the strange quark polarization in the proton.

The author thanks Professor P. Söding for useful conversations as well as for supplying a copy of Ref. [9].

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Figure Caption

Figure 1. The lowest-order diagram contributing to the hadronic tensor for the semi-inclusive Λ hyperon production in the deeply inelastic scattering of leptons off nucleons.

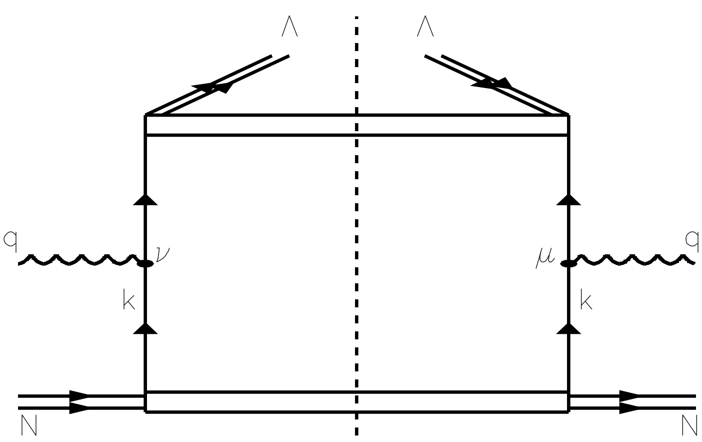

Fig. 1